

# Exploring the Next Generation Deep Space Network<sup>1,2</sup>

W. A. Imbriale, S. Weinreb, V. Jamnejad, and J. Cucchissi  
California Institute of Technology, Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, CA 91109  
818-354-5172  
imbriale@jpl.nasa.gov

**Abstract**— As the current 70-meter antennas are quite old (28–35 years) it is necessary to consider replacing these antennas in the near term as well as providing a capability beyond 70-meters in the future. A study was conducted that investigated the remaining service life of the existing antennas and considered alternatives for eventual replacement of the 70m-subnet capability. This paper examines several of the concepts considered and explores some of the options for the next generation Deep Space Network.

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## 1. INTRODUCTION

The key elements of the Deep Space Network (DSN), the 70m antennas, were built starting in the mid 1960's. They first became operational as 64m antennas in 1966–73. They were extended to 70m for Voyager's Neptune encounter in 1989. The antennas are now 28–35 years old. The 70m antennas are non-resilient, single points-of-failure. The remaining service life of the antennas is unknown but can be estimated.

A study was commissioned to 1) Investigate and estimate the remaining service life of the existing 70m antennas and 2) Investigate alternatives for backup and eventual replacement of the 70m subnet capability.

The study examined conventional antennas to replace the existing 70m antennas either by building a new 70m antenna or arraying four 34m antennas. The study also considered more novel approaches such as a large number of small (5–8m) reflector antennas, an array of flat plate antennas and a sphere antenna concept. The intent of the study was to identify the lowest cost solution.

In this paper the focus is on the SPHERE concept and the large number of small reflectors.

As initially conceived the Spherical Pair of High Efficiency Reflecting Elements (SPHERE) consisted of two 100m non-tipping spherical reflectors pointed at 30 and 70 degrees elevation. The antennas are fully rotatable in azimuth and switching between antennas is required as the spacecraft crosses 50 degrees elevation. The 100m diameter provides a 70m spot for all scans. It utilizes an Arecibo-style Gregorian feed system with a linear motion for elevation scan that covers  $\pm 20$  degrees elevation range. There is a major cost advantage over more conventional structures because there is no tipping of the large structure, no gravity effects (permits high frequency operation), a simple back-up structure, no counter weight, identical low cost panels, and a simple alignment procedure.

It was apparent from the study that replacing the 70m antennas is a costly venture and that there were many advantages to much larger apertures. For example, with a much larger aperture one could significantly increase the data rate or enable much smaller, lower cost spacecraft. With a much higher data rate there could be movies instead of images from Mars, high-resolution multi-spectral imaging, high-resolution synthetic aperture imaging of planets, and short-life, high data rate missions to hostile environments such as Venus or Europa. A very large area array could provide the necessary capability at an affordable cost. This could be accomplished using a large number of modest size (5–8m) reflectors.

The DSN 70m antennas are crucial for deep-space critical events, both for planned operations and anomalous unplanned operations. Examples of critical planned operations are: encounters, entry-descent-landing (Mars missions), limited-life vehicles (Solar Probe and Europa missions) and limited data return span (Cassini high-activity periods and NEAR Eros descent). Examples of anomalous unplanned operations are spacecraft emergency recovery (SOHO, NEAR, Voyager, and others) and saving damaged missions (Galileo). The DSN 70m antennas can significantly improve Space Science missions compared to the use of a 34m antenna.

The 70m capability, if baselined, can produce a  $\sim 4\times$  mission data return (at any given frequency) or reduce mission power, mass, volume and associated cost. But, the 70m antenna can only be baselined for a mission if it is reliable and backed up. Hence, the need for the 70m replacement study.

For the 70m replacement study, the following alternatives were considered [1]: 1) Evaluation of the existing 70m antenna, 2) A new 70m single aperture design, 3) An array of four 34m aperture antennas, 4) An array of ~5m apertures (dish), 5) An array of flat plate antennas, and 6) A SPHERE Antenna Concept.

## 2. EVALUATION OF THE EXISTING 70M ANTENNA

Two options were studied: 1) Life extension of the 70m antenna without a Ka-band upgrade, and 2) Life extension of the 70m antenna including Ka-band modifications.

A complete antenna structure model was updated for analysis of both strength and fatigue life using the current antenna use factor. The weakest sections were identified and proposals for retrofitting the suspected areas were investigated. Items to be overhauled included the subreflector positioner, azimuth drives, azimuth tangential links, azimuth bull gear, hydrostatic bearing, elevation bearing assembly, elevation bull gear, elevation drives and the radial bearing assembly. Costs and tasks for both a 10-year and 25-year extension were identified.

New technology for adding Ka-band included a new deformable subreflector with actuators, a much simpler, less expensive yet more accurate pointing instrument (replacement for the existing Master Equatorial instrument) and a new X/X/Ka-band feed. The X/X/Ka-band feed will replace the existing X-band feed and provide a Ka-band receive capability. The deformable subreflector will be used to compensate the Ka-band system for gravity distortion.

## 3. NEW 70M SINGLE APERTURE

The new antenna design will include state-of-the-art technology for gain recovery through gravity compensation and precision pointing at frequencies up to 50 GHz. This frequency range is sufficient to support the future Ka-band communication and the HEDS program. This design concept will provide and increase in performance of the existing 70m antennas. The primary configuration is for Ka-band (32 GHz) downlink and X-band downlink and uplink operations with allowance for future expansion to include Ka-band uplink and HEDS RF equipment. In addition, this antenna will be designed to allow for incorporating the existing 70m antenna RF equipment, to the maximum extent possible, should the existing 70m antennas become inoperable.

Key features of the new design (Figure 1) are a 70-meter-diameter main reflector, dual-shaped RF optics, a center-fed beam waveguide, feeds and front-end electronics located in alidade enclosures which rotate in azimuth, double elevation wheel and counterweights, electric drive for the azimuth wheels, an actuated main reflector surface for gravity compensation and a low profile concrete foundation. In addition, to provide precision blind pointing and focus corrections the following technologies should be incorporated: 1) Insulated and ventilated backup structure, 2) Thermal correction of pointing error and subreflector focus

error, 3) Wind sensor correction of pointing error and subreflector focus error, and 4) A metrology-controlled subreflector.

## 4. AN ARRAY OF FOUR 34M APERTURE ANTENNAS

This configuration is an array of four 34m BWG antennas to provide a 70m equivalent aperture. This option is considered the most mature as the antenna cost is readily available from the recent 34m antenna construction. The development of the downlink array technology was completed and tested for telemetry and tracking in Goldstone.

A problem was discovered when a high-power uplink (equivalent to 20 kW on the 70m antenna) was considered. If this uplink effective radiative power (EIRP) was to be produced with a single 34m antenna then a transmitter power of 80 kW would be required and the power density in the near field beam would exceed the aircraft safety standard of 10 mW/cm<sup>2</sup>. The EIRP could be achieved with a lower power density if more than one antenna had a transmitter and the array was properly phased; the required EIRP could be produced by 5 kW transmitters on each of the four antennas. The proper phasing can be obtained by a combination of calibration of transmitter phase using a spacecraft power monitor and knowledge of the geometric change in path length to each antenna as the pointing is changed. Atmospheric effects are small at X-band but are appreciable at Ka-band. Demonstration of X-band uplink phasing is being planned in the near future.

Future work proposed was to improve the antenna performance for support of the Human Exploration and Development of Space (HEDS) program by: 1) Providing a 100% solid reflector surface, 2) Better reflector surface RMS, 3) Higher drive capacity to handle the additional wind load due to solid panel utilization, 4) Better antenna pointing requirements, and 5) More reliable antenna design. It was also proposed to develop and demonstrate an uplink arraying technique.

## 5.0 AN ARRAY OF SMALL (5–8M) REFLECTOR ANTENNAS

An array of 350 6.1-m antennas is under construction in Hat Creek, California by the SETI Institute and University of California, Berkeley [3]. The array is known as the Allen Telescope Array (after a generous benefactor, Paul Allen), is planned for completion in 2005, and will have the equivalent area of a 114-m single telescope. Each antenna will utilize a log-periodic feed and low noise amplifier covering the entire 0.5 to 11 GHz frequency range.

A similar array, with 140 8-m antennas and higher performance narrow band receivers at 2.2, 8.4, and 32 GHz was considered for the 70-m replacement study (see Figure 2). There are a number of advantages to this approach:

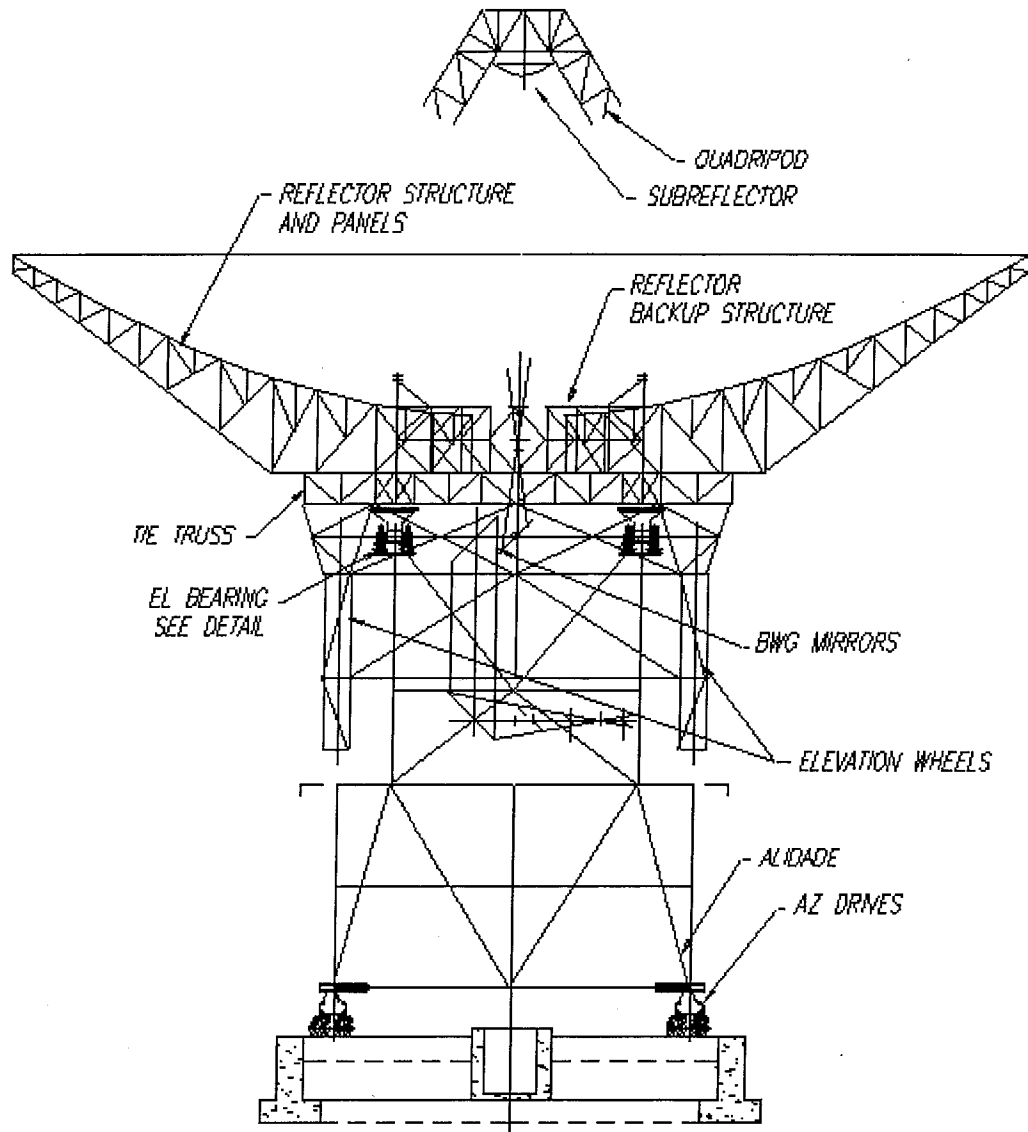


Figure 1 - Proposed 70-meter Replacement Antenna

- 1) Since the cost of antennas appears to vary in diameter,  $D^{2.7}$ , the cost per unit total area is less with an array of small antennas. For example, if a 70-m antenna cost \$100 M then the cost of 100 7-m antennas would be  $100 \times (0.1)^{2.7} = \$20$  M. However, the cost of the electronics for the array will be higher and for a given electronics cost per element. It can be shown that the minimum total cost for a given total area will be achieved with an antenna cost that is 2.86 times the electronics cost. This ratio is dependent only upon the antenna cost exponent, here assumed to be 2.7.
- 2) Higher data throughput by virtue of the flexibility and multiplicity of digital beam forming. Multiple beams within the main beam of the small antenna allows simultaneous communication with multiple spacecraft orbiting a planet. Subdividing the array into sub-arrays allows "just enough" communication with a number of spacecraft in totally different directions.
- 3) High reliability and availability by virtue of elimination of single-point failures. The array is sized to give the G/T and EIRP performance of a 70m even with 10% of the antennas being calibrated or maintained. Maintenance can be routine during a 40-hour work week.
- 4) Very high angular resolution—The proposed array has a beamwidth 14 times sharper than the beam of a 70m antenna. This allows new paradigms for spacecraft position determination. The beamwidth can be further sharpened by addition of outrigger antenna elements.

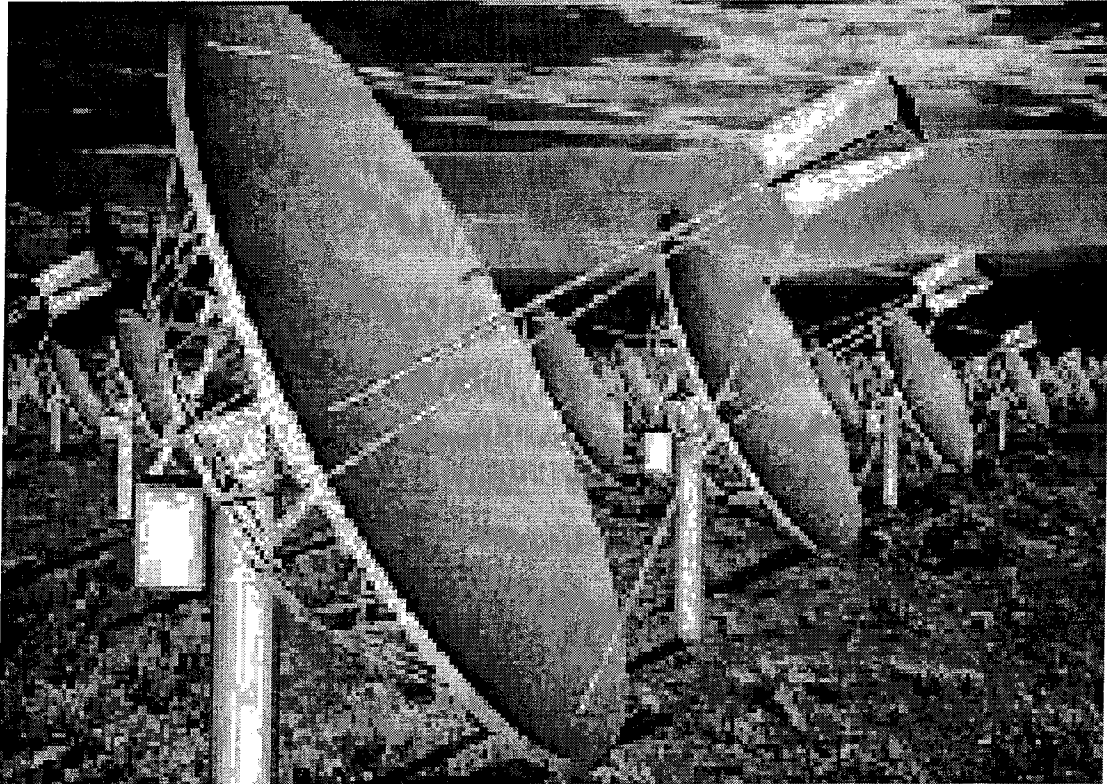


Figure - 2 An array of small reflectors

- 5) Extended frequency range—Small stamped solid aluminum antennas can operate at short wavelengths much more easily than large structures. Very wide bandwidth communication at frequencies as high as 100 GHz is feasible. The required number of antennas to produce a 62.4 dB/K G/T at 8.4 GHz (70 m equivalent) as a function of diameter is shown in Table 1.

**Table 1.** Required Number of Antennas as Function of Diameter

Antenna Diameter	5m	8m	12m
Elements required for 62.4 dB G/T at 8.4 GHz	328	128	58
Allowance for continuous calibration, 6%	20	8	4
Allowance for maintenance, 3%	10	4	2
<b>TOTAL REQUIRED ARRAY ELEMENTS</b>	<b>358</b>	<b>140</b>	<b>64</b>

There are a number of enabling technologies required to make a low cost array feasible such as: 1) Inexpensive, mass produced, stamped, parabolic dishes, 2) Multiple-frequency

or decade bandwidth feeds, 3) Low noise InP HEMT amplifiers, 4) Commodity priced 80 K cryogenics, 5) Wideband fiber optic links, 6) Satellite transmitter and timing calibration, and 7) Low cost solid-state high-power amplifiers. Whereas the technology for downlink arraying is quite well understood, the techniques for uplink arraying need to be developed.

## 6.0 AN ARRAY OF FLAT PLATE ANTENNAS

This array will consist of thousands of low cost, flat plate antennas arranged on the ground to enable signal detection from any direction within the hemisphere. The array orientation will be optimized to maximize the signal detection capability.

To provide a 70m capability with active planar phased arrays, millions of elements are required. Many alternative phased arrays including planar horizontal arrays, hybrid mechanical/electronically steered arrays, phased array of mechanically steered reflectors, multi-faceted planar arrays, phased array-fed lens antennas and planar reflect-arrays were compared and their viability assessed.

Although they have many advantages including higher reliability, near-instantaneous beam switching or steering capability, the cost of such arrays is presently prohibitive and it is concluded that the only viable array options at the present are the arrays of modest-sized reflector antennas.

## 7.0 SPHERE ANTENNA CONCEPT

The Spherical Pair of High Efficiency Reflecting Elements (SPHERE) original concept consists of two 100m non-tipping spherical reflectors pointed at 30 and 70 degrees elevation (see Figure 3). The antennas are fully rotatable in azimuth and it requires switching between antennas as spacecraft crosses 50 degrees elevation. The 100m-diameter provides a 70m spot for all scans and thus nearly equivalent performance to a 70-m parabolic reflector. It utilizes an Arecibo-style [3] Gregorian feed system with a linear motion for elevation scan that covers  $\pm 20$  degrees elevation range. There are major cost advantages over more conventional structures because there is no tipping of the large structure and no gravity effects (permits high frequency operation), a simple back-up structure, no counter weight, identical low cost panels, and a simple alignment procedure.

A spherical design was utilized previously for the Hobby Eberly 10-m optical telescope (HET) [4]. The cost of the HET is significantly less than an equivalently sized tipping structure such as the Keck telescope.

The Chinese are also considering a spherical antenna [5]. They are proposing a 500-m sphere with adjustable main reflector panels and a simple focal point feed. The main reflector panels are actuated for form a parabola for each direction of scan.

### *SPHERE design considerations – Feed Selection*

If instead of using an Arecibo-style feed system, it is possible to use a simple prime focus feed if the sphere antenna main reflector panels are actuated to form a parabola for each direction of scan as proposed by the Chinese [5]. This concept is displayed in figure 4. We consider a segment of a spherical reflector with a radius  $R$  and aperture diameter  $D_p$ , a portion of which with an aperture diameter  $D$  is carved out for use as a parabolic reflector. As discussed, this carved out portion of the spherical surface is slightly reshaped to conform to a parabolic surface. By selecting different portions of the spherical reflector and moving the feed accordingly on a circular curve with its center at the sphere center, we can scan the antenna beam.

For a maximum scan of  $\pm \theta_s$  and for the half subtended angle from the center to the parabolic portion of the surface,  $\theta_e$ , we can write

$$\begin{aligned} R \sin(\theta_e) &= D/2 \\ R \sin(\theta_e + \theta_s) &= D_p/2 \end{aligned} \quad (1)$$

These two equations can be solved to obtain

$$\begin{aligned} \tan(\theta_e) &= \frac{D \sin(\theta_s)}{D_p - D \cos(\theta_s)} \\ R &= \frac{D/2}{\sin(\theta_e)} \end{aligned} \quad (2)$$

Therefore, given  $D_p$ ,  $D$ , and maximum scan angle  $\theta_s$ , the radius of the sphere and the subtended angle are uniquely determined. Now it can be shown that the optimum position of the feed for minimizing the surface error from the sphere to the paraboloid is at a point about 0.45-0.5  $R$  from the vertex. Specifically, in one study [6] it is shown that an optimum focal length,  $F_{op}$ , minimizing the total error is given by

$$F_{op} = \frac{1}{4} (R + \sqrt{R^2 - (D/2)^2}) \quad (3)$$

This can be used to obtain

$$\tan(\theta_p/2) = 2 \tan(\theta_e/2) \quad (4)$$

In which  $\theta_p$  is the half subtended angle from the focal point to the parabola edge. But it is easy to show that

$$\tan(\theta_p/2) = \frac{1}{4(F/D)} \quad (5)$$

Therefore

$$(F/D) = \frac{1}{8 \tan(\theta_e/2)} \quad (6)$$

Notice that the optimum given in [6] is only for ignoring the illumination taper and with taper the optimum focal length is somewhat larger. From (2) and (6) we solve for  $F/D$  as a function of  $D_p$  for a given scan angle  $\theta_s$ .

The results are plotted in Figure 5. In the figure we consider two cases one for  $\pm 20^\circ$  maximum scan and one for  $\pm 40^\circ$  scan. The first one would require two reflectors for complete azimuth coverage (0-80) while with the second one only one would be required for full coverage.

It can be seen that for a 100-meter sphere aperture the optimum  $F/D$  is 0.4 for a maximum scan of 20 degrees. The  $40^\circ$  scan case would require an aperture of 118 meters for the same  $F/D$  of 0.4.

For 120-meter sphere aperture, the optimum  $F/D$  is 0.59 for the  $20^\circ$  scan and 0.41 for  $40^\circ$  scan case.

For the given  $F/D$  range, a candidate design covering all three DSN frequencies of S, X and Ka band would be a Coaxial Cavity Antenna design by Tim Holtzheimer of Raytheon [7] which can cover from 2 GHz to 40 GHz band as shown in Figure 6.

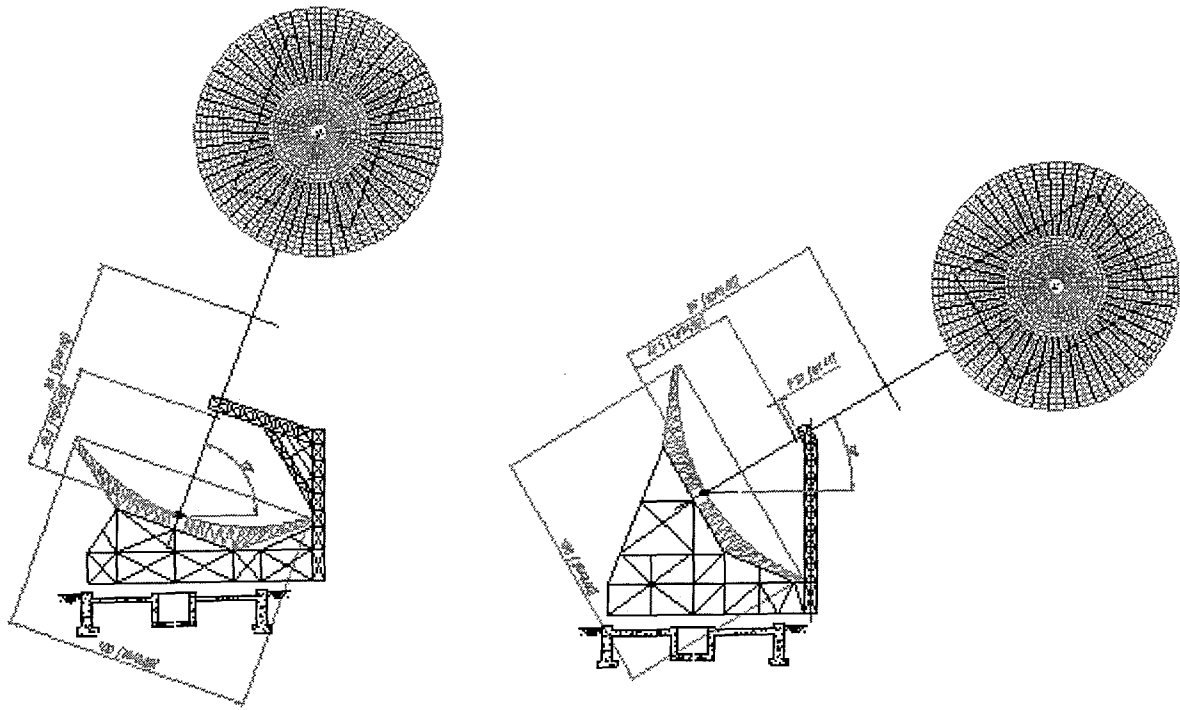


Figure 3 - SPHERE Concept Drawing

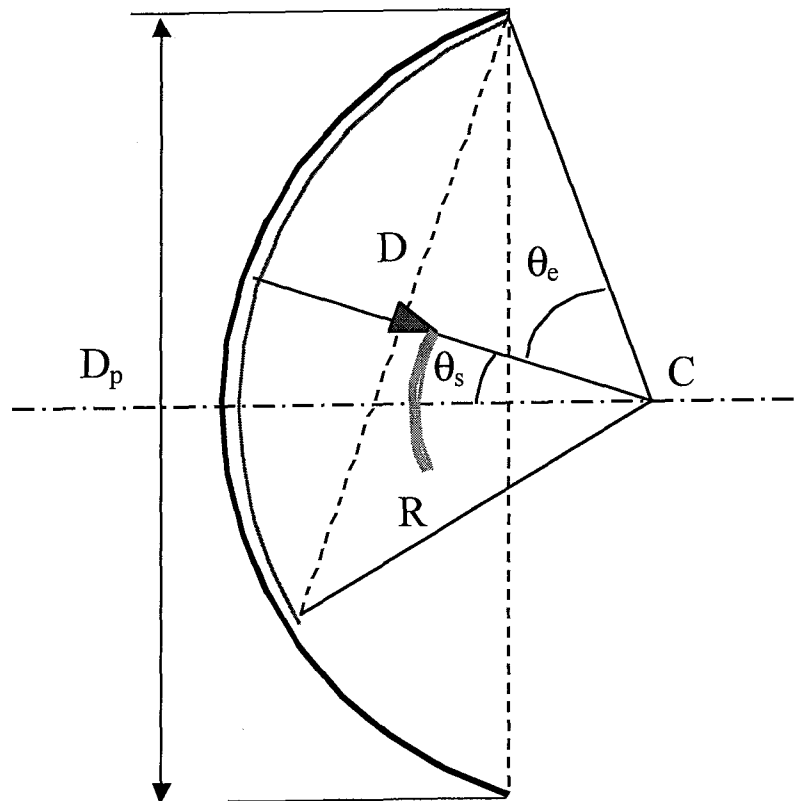


Figure 4 - Sphere Geometry

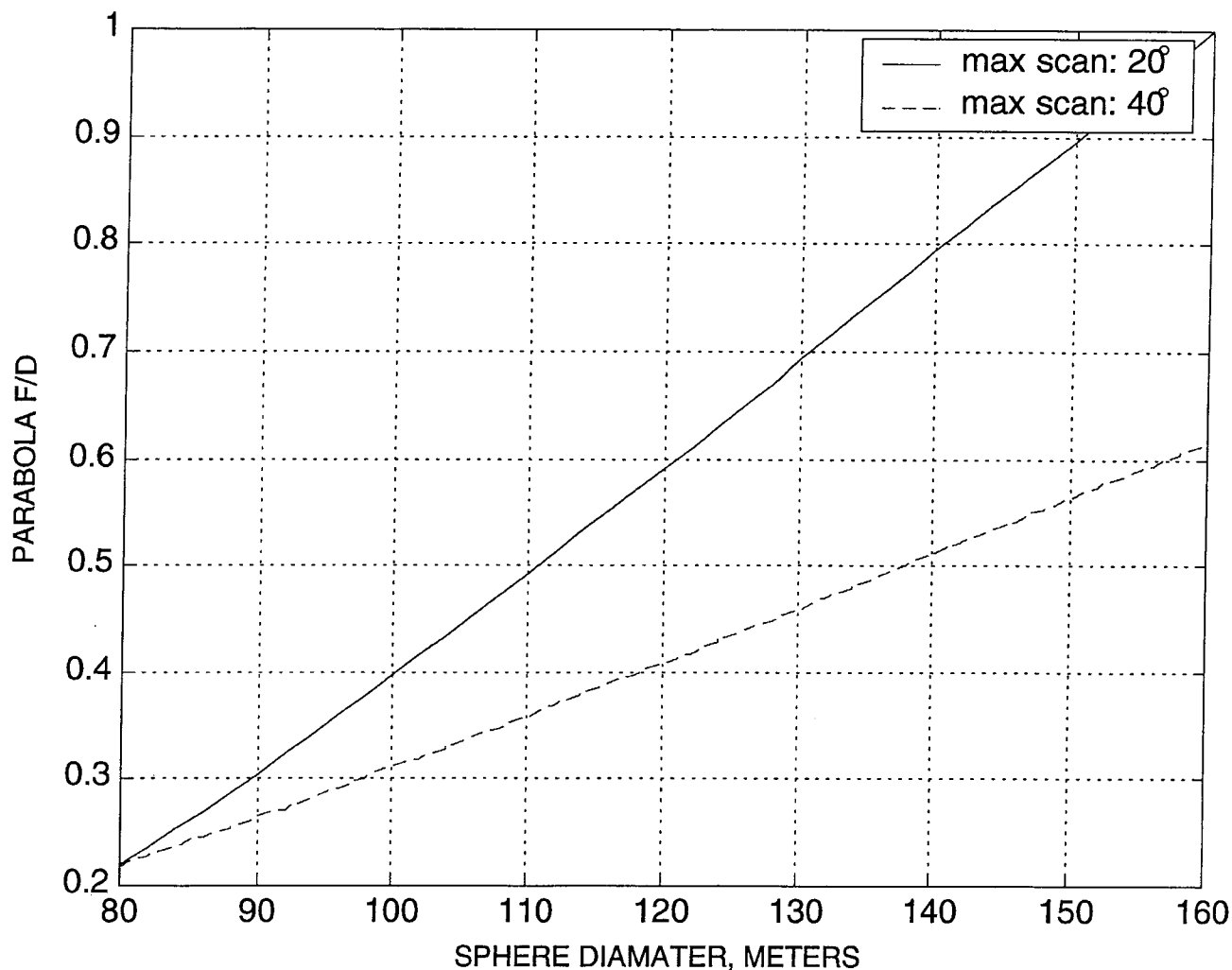


Figure 5 - Optimum paraboloid F/D as a function of the sphere aperture for scan angles of 20° and 40°

#### *Sphere design considerations – one antenna with no panel actuators*

Because the actuator motion of the panels required to form a parabola from the sphere geometry would be fairly large (~20 cm), there would be a significant advantage to have a simple prime focus feed system instead of either actuating the panels or using the large two mirror Arecibo feed system. The spherical aberration phase errors can be removed by the use of an appropriately shaped concave secondary reflector, rigidly attached to and rotating with the feed system. The current proposed SPHERE system is to use this feed system with only one reflector to cover the elevation angle range.

### 8.0 CONCLUSIONS

The present DSN capability places severe constraints on deep space science due to data rate limits and spacecraft antenna and power requirements. The DSN is saddled with aging facilities, which are costly to maintain and is faced with increasing demands for more complex and data-rich

missions. Long-range development of the DSN is concentrated in optical technology, which has limitations due to pointing requirements and high quantum-limited noise. It is not an either/or proposition, however. There is likely to be a continued need for an RF link from the ground for the foreseeable future.

It is exciting to speculate what a 100 times increase in aperture could do for space science or spacecraft design, possibly enabling missions not yet envisioned. However, the only way to accomplish this is through the use of arrays of low-cost, modest-sized reflector antennas. The radio astronomy community believes that a revolutionary new instrument at radio wavelengths is possible, one with an effective collecting area more than 30 times greater than the largest telescope ever built. Such a telescope will reveal the dawn of galaxy formation, as well as a plethora of other new discoveries in all fields of astronomy. Vigorous technological developments in computing and radio frequency devices make it possible for such a telescope to be built within the next decade, and the international radio astronomical community is proposing that such a telescope,

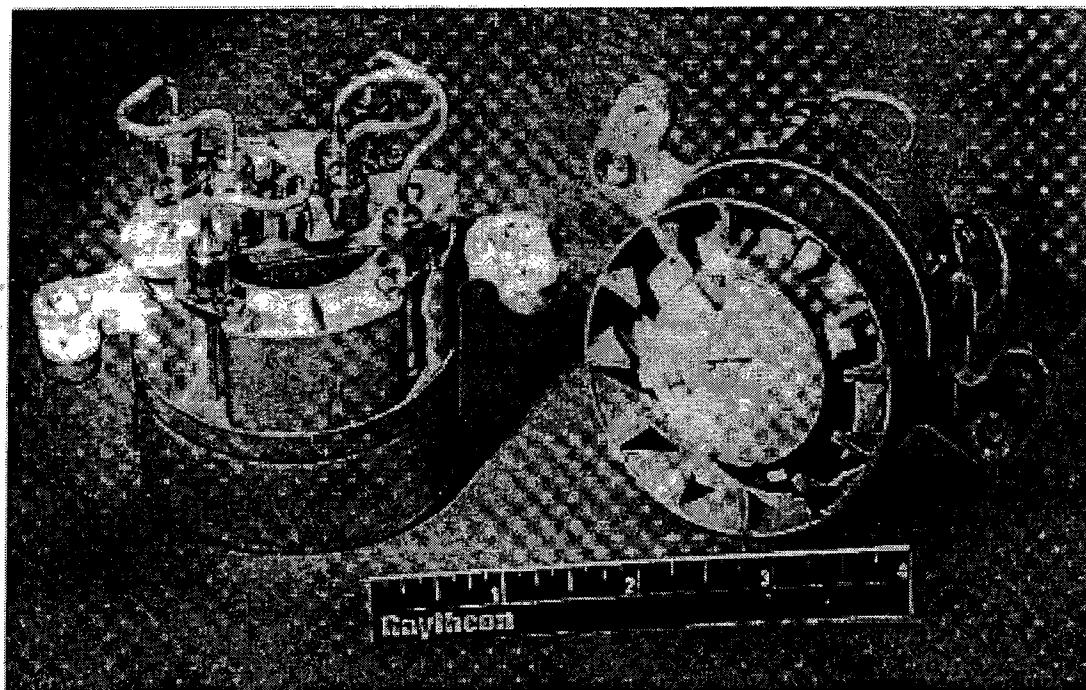


Figure 6 - Picture of the Raytheon Coaxial Cavity feed

with a million square meters of collecting area, be the next major radio telescope to be built. The project has acquired the appellation, the Square Kilometer Array [8].

JPL, always a forward-looking enterprise, should take advantage of the technology developments in the radio astronomy and build its own SKA. It would enable the next generation of spacecraft to continue its expansion into the universe with more "first of a kind" missions.

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**William A. Imbriale** received the BS degree in engineering physics from Rutgers University in 1964, the MS degree in electrical engineering from the University of California, Los Angeles, in 1966, and the Ph.D. degree from the University of Illinois in 1969.

Dr. Imbriale is a Senior Research Scientist in the Communications Ground System Section of the Jet





*Propulsion Laboratory in Pasadena, California. He is leading the activities for several advanced technology developments for large ground station antennas as well as supporting advanced technology in lightweight spacecraft antennas and submillimeter wave instruments. Previously, Dr. Imbriale was the Assistant Manager for Microwaves in the Ground Antennas and Facilities Engineering Section, and was responsible for all the technical activities associated with the RF design and development of the Large Ground-Based antennas of the DSN. In 1991, he was on a six-month temporary assignment as a Foreign Research Fellow at the Institute of Space and Astronautical Science in Japan working on mesh deployable spacecraft antennas and beamwaveguide ground antennas.*

*During the 1980's he was Manager of the Radio Frequency and Microwave Subsystem Section, responsible for the research, development and implementation of the RF and microwave subsystems used in the DSN. He was manager during the critical period of equipment delivery for DSN support to the voyager mission, which included upgrades to virtually all telecommunications subsystems.*

*Prior to joining JPL in 1980, Dr. Imbriale was employed at the TRW Defense and Space Systems Group where he was the Subproject Manager for the Antennas for the Tracking and Data Relay Satellite Systems (TDRSS) program.*

*Dr. Imbriale is a Fellow of the IEEE, a member of the International Union of Radio Science Commission B, and a member of the Sigma Xi, Tau Beta Pi, and Eta Kappa Nu honor societies. He was a member of the Ad-Com Committee of the IEEE Antennas and Propagation Society, and general chairman of the 1995 International IEEE AP-S International Symposium held in Newport Beach, California. He has lectured and taught engineering courses at several local schools, including UCLA and USC. He is also a consultant to industry on all aspects of antenna analysis and design. From 1993 through 1995 he was a Distinguished Lecturer for the Antennas and Propagation Society speaking on Beamwaveguide Antennas and the Evolution of the Deep Space Network Antennas. He has also won two best paper awards.*